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Effects of Nitrogen fertilisation and stocking rates on soil erosion and water infiltration in a Brazilian Cerrado farm

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A R T I C L E I N F O

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A B S T R A C T

Ever-increasing water-food-energy demand has led to the depletion of soil resources by mainly inadequate grazing practices. Nevertheless, the effects of different grazing practices on hydrological and soil erosion processes have not yet been well-understood. Therefore, we investigated the influence of different Nitrogen application doses and stocking rates in a pasture under rotational stocking (RS) on soil erosion and water infiltration in the Brazilian Cerrado region. The experimental area was a *Panicum maximum* pasture and was divided into three treatments with N applications of 100, 200, and 300 kg ha^{-1}, which respectively allowed three stocking rates from 2014 to 2018: 3 (RS-3), 4.1 (RS-4), and 5 AU ha^{-1} (RS-5). We respectively adopted start and stop grazing heights of 80–90 and 40–50 cm (forage height) in all treatments. To evaluate infiltration and soil erosion, we performed 28 rainfall simulations with intensities ranging from 73.5 to 93.5 mm h^{-1} in plots of 0.7 m^2 from November 2017 to February 2018. The simulations were carried out in random sites inside the central paddocks of each treatment comprising four repetitions in each treatment under vegetation and bare soil. We found stable water infiltration (SIR) and soil loss (SL_w) ranging from 65.5 to 87.2 mm h^{-1} and from 0.03 to 0.15 mg s^{-1} m^{-2}, respectively. SIR and SL_w under RS-5 were respectively 33% greater and 78% lower than under RS-3 despite the 67% higher stocking rate in RS-5. We found that higher stocking rates at optimal grazing pressure did not deteriorate water infiltration and soil erosion. Our findings reveal an opportunity for a 5-fold productivity increase while reducing soil degradation since adaptive stocking rates are supported by grazing processes along with an increase in N fertiliser dose to increase vegetation cover.

1. Introduction

Livestock stocking rates have increased in some parts of the world to feed the ever-increasing population and the demand for water-food-energy. It has led to soil compaction and deterioration in soil physical properties, particularly water storage and water supply (Hamza and Anderson, 2005). Suitable soil is one of the most essential factors determining food security (de Vrese et al., 2018), and it is estimated that up to 780 million ha will be degraded by soil erosion in Latin America and the Caribbean by 2050 (Premanandh, 2011). Brazil has an estimated annual absolute land productivity loss of 6.4% of arable lands due to soil depletion and erosion, resulting in a decrease of 385 thousand tons in the livestock production (Sartori et al., 2019). The main benefit from intensive grazing management is the possibility of intensifying production, reducing costs, and saving area; however, there is a lack of studies on the environmental impact of intensive grazing regarding soil erosion and water infiltration.

Stocking methods and management strategies aim at achieving and maintaining desired management criteria according to specific goals. One of the most frequent strategies found in the literature is rotational

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stocking. It focuses on maximising the production level and uses recurring periods of grazing and rest among a number of paddocks, usually from 4 to 30, one at a time allowing post-grazing recovery. In the 18th century, James Anderson described the principle of rotational stocking (Voisin, 1959). Most recently, intensive short-duration management has been introduced to fulfil the societal and environmental needs (Savory, 1983; Savory and Parsons, 1980).

The Savory grazing method (SGM), or holistic resource management, was proposed by Allan Savory in 1980. Allen et al. (2011) state that holistic resource management is a philosophy and should not be used as a name for any stocking method. SGM consists of three main principles that sometimes are adopted and discussed in the literature as separate stocking methods and management strategies: the method should apply (i) holistic management, which means that livestock must be managed as an integral part of the ecosystem mimicking ancient wild herds; (ii) time-controlled grazing; and (iii) should generally use a cell grazing structure, which is a fencing layout with radiating fence lines (Savory and Parsons, 1980). Nonetheless, the SGM implementation and classification are controversial as, three years after the method proposal, Savory stated there are myths and misconceptions about the method (Savory, 1983). Furthermore, the SGM lacks substantial support for the improvement of vegetation and soil properties due to its adaptive and flexible nature (di Virgilio et al., 2019).

Rotating livestock is time-dependent on grazing heights, defined as adopted forage heights to start and stop grazing, to prevent overgrazing and overstocking (Teague, 2018). Otherwise, trampling by livestock compacts the soil surface, decreasing water infiltration. However, only adjusting stocking rates is insufficient to prevent overgrazing. One of the alternatives to avoid land degradation is to use fertilisers to intensify production. Nitrogen fertilisation, when used according to plant demand, is considered essential for increasing forage accumulation as it directly influences vegetation growth (Garcez and Monteiro, 2016). Although the USDA Natural Resources Conservation Service (NRCS) recommends rotational stocking as a best management practice, its effectiveness for decreasing runoff and erosion needs to be assessed.

Previous studies show that land cover and land use changes in Brazil have increased soil erosion (Oliveira et al., 2015a, 2015b). To reduce soil erosion rates, soil and water loss need to be assessed for prioritisation and formulation of proper land management techniques for making agronomic and economic advances in grazing management more sustainable. Therefore, there is a need to investigate how intensive grazing management affects runoff and soil loss. However, few studies have been carried out experimentally addressing water infiltration and soil erosion in intensively managed pasturelands; there are several studies on agronomic and economic efficiencies (Euclides et al., 2016; Mihailescu et al., 2015) but there is a lack of studies on the influence of those systems on soil degradation.

The objective of this study is to investigate the influence of adopting different stocking rates in a pasture under rotational stocking on soil erosion and water infiltration in an Oxisol site (35% of clay) located in the Brazilian Cerrado. Different stocking rates were obtained as a consequence of applying three Nitrogen fertiliser concentrations to provide minimum conditions for forage maintenance. Our findings contribute to fulfilling the environmental gap regarding intensive production so that identifying sustainable land uses will stimulate the livestock sector growth. Thus, the study shows the importance of having adaptive management to ensure the sustainability of agriculture, mainly having grazing management that envisions optimal decision variables to maximise productivity and minimise negative environmental impacts.

2. Material and methods

2.1. Study Area

Embrapa Beef Cattle has developed an experiment whereby intensive grazing management has been studied since 2008. Embrapa is located in Campo Grande, Mato Grosso do Sul (Fig. 1), at an altitude of 566 m. The experimental area has 13.5 ha and consists of a *Panicum maximum* cv. Mombaça guineagrass pasture. *Panicum* spp. are recognised for their forage accumulation with high productivity, nutritional value, and satisfactory animal performance (Jank et al., 2010).

According to Köppen, the climate is *Aw*, which is a rainy tropical climate zone with a mean annual temperature of 22 °C and mean annual precipitation of 1500 mm yr^{-1}. The soil is classified as Dystrophic Red Latosol (Oxisol), containing about 35% of clay at 0–20 cm depth. It is the main soil order in Brazil, covering about 32% of the territory and 45% of the Brazilian Cerrado (Santos et al., 2011). Studying livestock production on this soil type and biome is paramount since there have been intensive rates of clearing native land cover to pasturelands (Espírito-Santo et al., 2016).

2.2. Experimental Design and Treatments

The pasture area was divided into three experimental units according to the annual Nitrogen application rate (Urea fertiliser): 100, 200, and 300 kg N ha^{-1}. Each experimental unit has three replications (1.5 ha), except for the units with 200 kg N ha^{-1} which has two, in a randomised complete block design; each replication contains six paddocks of 0.25 ha (Fig. 2). We adopted the stocking methods of rotational stocking (RS) and put-and-take stocking (Mott and Lucas, 1952). The latter method consists of using variable animal numbers with a periodic adjustment to maintain an optimal grazing pressure (where appropriate, we adopted the grazing terminology as in Allen et al. (2011)).

Nellore tester steers of 15 months old (avg w 300 kg) were used to adjust the stocking rate to meet the start grazing and stop grazing heights (put-and-take method). The tester steers were weighed every 28 days after 16 hours of fasting, and the stocking rate was obtained by the average live weight of the steers corrected by the number of days they spent grazing each paddock. The livestock stayed in a paddock until forage reached the post-grazing height of 40–50 cm. Similarly, they were allowed to graze another paddock when its forage reached the pre-grazing height of 80–90 cm. The pre-grazing height was adopted based on previous studies that found the ideal period to interrupt regrowth, which is associated with a canopy light interception of 95% of photosynthetically active radiation (PAR) (Carnevalli et al., 2006; Silva et al., 2009).

Overall, during the period from 2014 to 2018, we observed that the stocking rate increased as the Nitrogen concentration increased (Table 1). The units that received 100, 200 and 300 kg N ha^{-1} respectively presented an average stocking rate of 3 AU ha^{-1} (RS-3), 4 AU ha^{-1} (RS-4), and 5 AU ha^{-1} (RS-5). In this study, we refer to treatments according to the average stocking rate observed in each unit. The rest period varied from about 25 to 30 days while the grazing period ranged between 5 and 7 days, both according to the time for reaching heights to begin and end grazing; higher N doses led to less resting time.

To maintain the Nitrogen concentration in each treatment, supplementary doses were applied based on physical and chemical soil analyses in 2014/2015, 2015/2016, and 2016/2017. Additionally, all treatments were fertilised with 80 kg ha^{-1} of P_2O_5 and K_2O in 2014/2015, 2015/2016, and 2016/2017 based on the average soil chemical characteristics for the 0–20 cm layer (Table 2). The last fertilisation occurred in March 2017, and we carried out the tests from November 2017 to January 2018. Thus, we analysed the residual effect of the Nitrogen doses applied on forage mass production, indirectly affecting the stocking rate, water infiltration, and soil erosion. It reflects the decrease in stocking rates in 2017, observed in Table 1.

We carried out the rainfall simulations in both the experimental area and the Cerrado (*cerrado sensu stricto*) to compare the native vegetation with this agricultural land use and management. The simulation tests were completely randomised with four repetitions in each treatment; after each simulation, we removed the vegetation and performed the test again to evaluate the vegetation effect on water infiltration and soil loss.

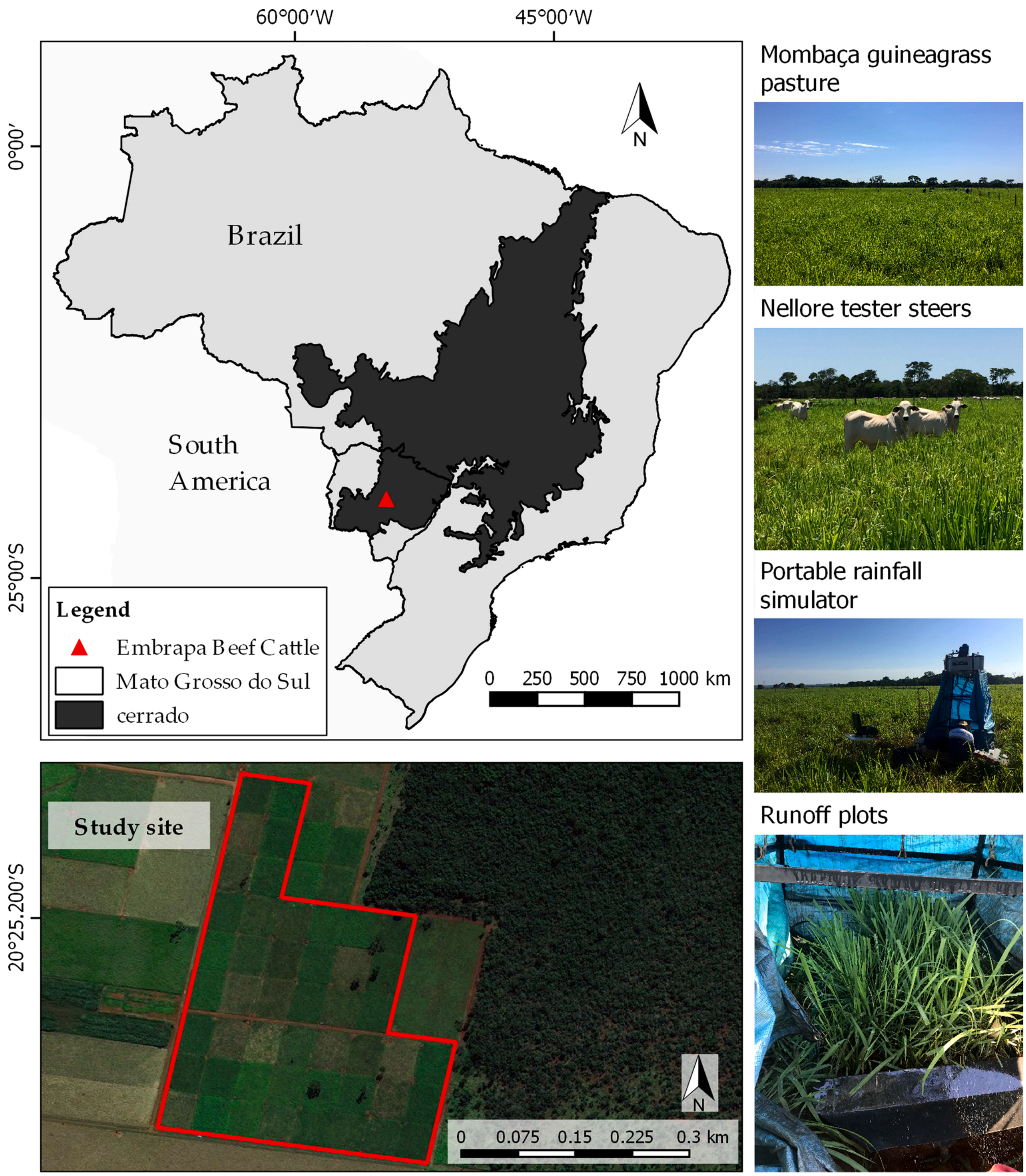

Fig. 1. Location of the study site and photographs of paddocks, rainfall simulator, and plots.

Results from bare soil plots provide reference values for soil erosion reduction in each treatment.

2.3. Data collection

We carried out 28 rainfall simulations in the study area from November 2017 to February 2018. We used a portable rainfall simulator (Alves Sobrinho et al., 2008) with runoff plots of 0.7 m^2 and 2-mm thick galvanised iron sheets. We performed the rainfall simulations in random sites inside the central paddocks of each treatment (as illustrated in Fig. 2). We designed rainfall simulations on vegetation cover and bare soil.

The rainfall simulator is equipped with two parallel Veejet 80.150 flat spray nozzles that provide 2-mm raindrops when placed at a height of 2.3 m with a working pressure of 35.6 kPa. Additionally, we calibrated the equipment to apply a constant rainfall intensity of 89.6 ± 9.5 mm h^{-1} in the RS-3, 73.5 ± 4.3 mm h^{-1} in the RS-4, 93.5 ± 0.4 mm h^{-1} in the RS-5, and 73.9 ± 2.2 mm h^{-1} in the Cerrado until reaching a constant infiltration rate (stable infiltration rate – SIR) (Panachuki et al., 2011). Since we performed pre-wetting at least 12 hours before every rainfall simulation to ensure uniform soil moisture content (Cogo et al., 1984), SIR was reached during one-hour rainfall events. Soil bulk density (BD) was measured below and out of the Mombaça grass clumps. Moreover, we measured the initial and final soil moisture content in each rainfall simulation test (Table 3). The initial soil moisture content was measured on the pre-wetted soil.

The observed infiltration rate was obtained by the difference between the rainfall intensity and surface runoff, measured for one minute at a time interval of 1 minute. Additionally, the observed infiltration was adjusted to Horton's model (Horton, 1939, 1933) using non-linear

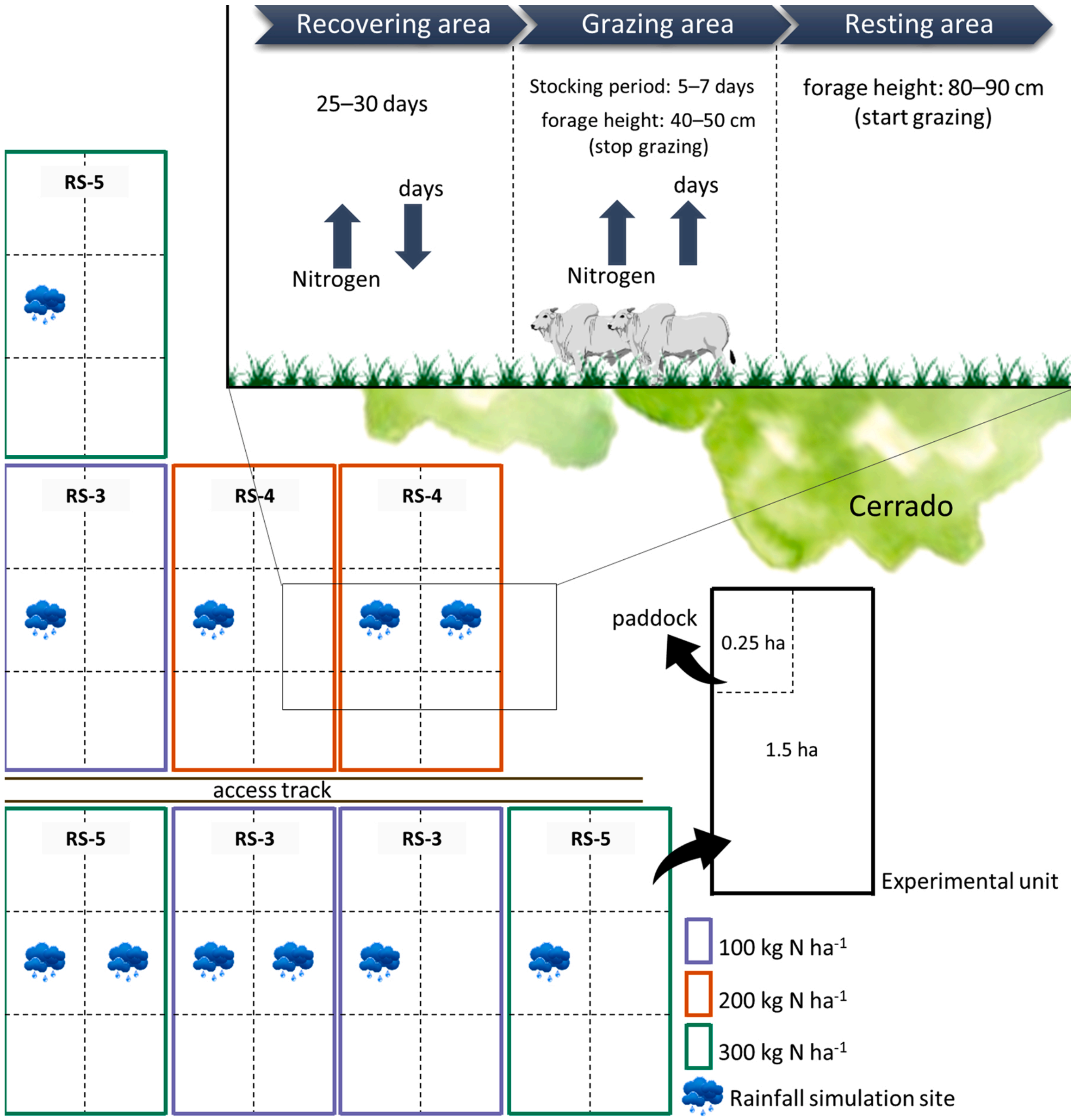

Fig. 2. Sketch of the experimental area and the tester steer rotation scheme.

Table 1
Stocking rates established in RS-3, RS-4, and RS-5 from 2014/2015 to 2017/2018.

Period	Stocking rates (AU ha^{-1}) according to Nitrogen concentration		
	RS-3 (100 kg N ha^{-1})	RS-4 (200 kg N ha^{-1})	RS-5 (300 kg N ha^{-1})
2014/2015	3.4	4.7	5.7
2016/2017	2.9	4.6	5.3
2017/2018	2.7	3.1	4.0

Note: AU is the animal unit where 1 AU equals 450 kg live weight.

Table 2
Average soil chemical analysis for the 0–20 cm soil layer in 2017.

Soil chemical characteristics	RS-3	RS-4	RS-5
OM (mg L^{-1})	4.0	3.8	3.9
pH ($CaCl_2$)	5.6	5.6	5.5
P (mg L^{-1})	3.9	6.5	3.7
K (cmol L^{-1})	0.3	0.3	0.3
Ca (cmol L^{-1})	2.4	2.6	2.2
Mg (cmol L^{-1})	1.3	1.3	1.1
Al (cmol L^{-1})	0.01	0.01	0.01
Al+H (cmol L^{-1})	2.84	3.10	3.37
Bases sum (cmol L^{-1})	4.0	4.1	3.7
CEC (cmol L^{-1})	6.9	7.2	7.0
Base saturation (%)	58	57	52

Note: CEC is cation-exchange capacity; RS-3 is rotational stocking under an average stocking rate of 3 AU ha^{-1} and fertilisation of 100 kg N ha^{-1}; RS-4 is rotational stocking under an average stocking rate of 4 AU ha^{-1} and fertilisation of 200 kg N ha^{-1}; RS-5 is rotational stocking under an average stocking rate of 5 AU ha^{-1} and fertilisation of 300 kg N ha^{-1}.

regression (Generalised Reduced Gradient method). Horton's equation tends to be more adequate for estimating the water infiltration rate (Almeida et al., 2018), and it is an empirical expression widely used in hydrology as a function of the corresponding time (Assouline, 2013):

$$f(t) = f_c + (f_0 - f_c)exp^{-kt}$$

Table 3
Mean physical characteristic values in 2017/2018.

Treatments	θ_i (%)	θ_f (%)	BD[a] (g cm^{-3})	BD[b] (g cm^{-3})
RS-3	16	28	1.28 ± 0.04	1.32 ± 0.06
RS-4	27	31	1.33 ± 0.05	1.40 ± 0.14
RS-5	20	27	1.22 ± 0.08	1.28 ± 0.10
Cerrado	19	22	0.89 ± 0.01	-

Note: θ_i and θ_f are initial and final gravimetric soil water content; BD[a] is Soil Bulk Density below Mombaça grass clumps; BD[b] is Soil Bulk Density out of Mombaça grass clumps; RS-3 is rotational stocking under an average stocking rate of 3 AU ha^{-1} and fertilisation of 100 kg N ha^{-1}; RS-4 is rotational stocking under an average stocking rate of 4 AU ha^{-1} and fertilisation of 200 kg N ha^{-1}; RS-5 is rotational stocking under an average stocking rate of 5 AU ha^{-1} and fertilisation of 300 kg N ha^{-1}.

where $f(t)$ is the estimated instant infiltration rate (mm h^{-1}); t is the infiltration time (min); and f_0 and f_c are the observed initial and stable infiltration rate (SIR) (mm h^{-1}) with a decay constant of k. To assess the error of the model's adjustment, we performed the Standard Error of Regression (S).

For soil loss, we measured the runoff volume for 1 min every 2 minutes, and we collected one sample out of three from those measures in one-litre containers. The total weight of each container was determined, and the runoff samples (water plus sediment) were oven-dried at 70 °C for a necessary period to ensure total water evaporation and constant dry mass weight. Thus, soil loss for each simulation was calculated as the total sediment load divided by the plot area (mg s^{-1} m^{-2}). Additionally, to compare soil loss from the different rainfall intensities applied, we weighted the measured soil loss of each treatment using the Rainfall Erosivity Index from the Universal Soil Loss Equation (USLE) (Wischmeier and Smith, 1978) as:

$$SL_w = SL_i \times FEI_{30i} \Big/ \sum FEI_{30}$$

where SL_w is the erosivity-weighted value of soil loss (mg s^{-1} m^{-2}); SL_i is the measured soil loss in each simulation (i, i = 1 to 4) (mg s^{-1} m^{-2}); FEI_{30i} is a fraction of the Rainfall Erosivity Index (EI_{30}) from all simulations as:

$$FEI_{30i} = EI_{30i} \Big/ \sum EI_{30}$$

where, in this study, EI_{30i} is the rainfall erosivity index for each rainfall simulation, calculated by the product of the rain intensity applied in each simulation event and the kinetic energy.

2.4. Statistical analysis

To compare the effect of different stocking rates on water infiltration and soil loss, we performed the Scott Knott test (α = 0.05) in vegetated and on bare soil conditions. The mean SIR and soil loss from each treatment were divided into groups without overlapping by using a probabilistic approach with an asymptotic χ^2 distribution. Scott Knott is a hierarchical clustering algorithm for exploratory analysis; it separates treatments into distinct groups without overlapping. Some studies have used this statistical test and obtained satisfactory results (Almeida et al., 2018; Sena et al., 2002; Sone et al., 2019). The analysis was performed by using the Scott-Knott package (Jelihovschi et al., 2014) in the statistical and computing environment R (R Core Team, 2014).

3. Results

We verified a suitable model fit of the Horton's model with standard errors smaller than the standard deviations of the rainfall intensities applied. Overall, the standard error of the regression (S) in both treatments varied from 0.1 to 3.3 mm h^{-1} for vegetation cover conditions and from 0.3 to 4.7 mm h^{-1} for bare soil conditions (Table 4). Some adjustments using Horton's equation were more concave than others, and therefore S was higher than 1. Next, we tested our water infiltration and soil erosion results for variance and identified similarities among the treatments by using cluster analysis.

The main impact the FEI correction has on the results was making soil loss between treatments more comparable. For instance, rainfall intensity applied in all simulation on RS-3 was, on average, higher (average rainfall intensity of 90 mm h^{-1}) than in RS-4 (average rainfall intensity of 74 mm h^{-1}). Observing the measured values, soil loss was nearly 4 times higher in RS-3 compared with RS-4 while there was no difference between the soil loss found in RS-3 and in RS-4 (Scott-Knott test α = 0.05) after the FEI correction (Table 5).

3.1. Comparing the effects of different stocking rates on water infiltration and soil erosion

Considering vegetation cover, we found the highest average stable infiltration rate (SIR) of 87.2 ± 1.7 mm h^{-1} under RS-5 while average SIR for RS-3, RS-4, and the Cerrado did not differ (α = 0.05) (Fig. 3 A). Nevertheless, we noted that the weighted soil loss (SL_w) in vegetated plots was not statistically different (α = 0.05) even though the observed SL_w tends to decrease from RS-3 to RS-5 (Fig. 3 B). Compared with RS-3,

Table 4
The Horton's equations of each treatment considering vegetated and bare soil plots.

Treatments	N	Vegetation cover		Bare soil	
		Horton's equation	S (mm h^{-1})	Horton's equation	S (mm h^{-1})
Cerrado	1	$i = 73.1 + 2.2 \times e^{-0.02t}$	0.1	$i = 74.9 + 3.8 \times e^{-0.10t}$	0.3
	2	$i = 70.0 + 2.0 \times e^{-0.01t}$	0.1	$i = 68.3 + 10.8 \times e^{-0.05t}$	0.7
	3	$i = 74.6 + 1.4 \times e^{-0.05t}$	0.1	$i = 69.0 + 10.6 \times e^{-0.04t}$	0.4
	4	$i = 66.6 + 5.0 \times e^{-0.05t}$	0.4	$i = 65.2 + 21.3 \times e^{-0.10t}$	2.6
RS-3	1	$i = 67.3 + 16.4 \times e^{-0.04t}$	1.5	$i = 32.2 + 51.4 \times e^{-0.22t}$	4.1
	2	$i = 72.8 + 15.2 \times e^{-0.37t}$	1.1	$i = 41.6 + 36.5 \times e^{-0.29t}$	3.7
	3	$i = 65.5 + 13.0 \times e^{-0.09t}$	0.6	$i = 30.2 + 38.5 \times e^{-0.07t}$	3.2
	4	$i = 56.3 + 36.3 \times e^{-0.06t}$	3.3	$i = 40.9 + 59.0 \times e^{-0.19t}$	4.7
RS-4	1	$i = 72.1 + 4.0 \times e^{-0.12t}$	0.5	$i = 42.0 + 22.0 \times e^{-0.43t}$	1.8
	2	$i = 63.7 + 9.5 \times e^{-0.36t}$	1.4	$i = 34.6 + 42.1 \times e^{-1.36t}$	3.4
	3	$i = 50.4 + 24.7 \times e^{-0.08t}$	2.1	$i = 31.4 + 34.2 \times e^{-0.22t}$	3.0
RS-5	1	$i = 87.0 + 2.4 \times e^{-0.03t}$	0.9	$i = 64.9 + 25.0 \times e^{-0.22t}$	3.3
	2	$i = 85.7 + 4.2 \times e^{-0.16t}$	1.7	$i = 60.9 + 32.7 \times e^{-0.15t}$	3.3
	3	$i = 89.0 + 1.3 \times e^{-0.08t}$	0.5	$i = 70.3 + 2.0 \times e^{-0.18t}$	0.5

Note: Different letters indicate statistical different groups (α = 0.05). N is the repetition; S is the Standard error of the Regression (mm h^{-1}); SIR is the stable infiltration rate (mm h^{-1}); sd is standard deviation; RS-3 is rotational stocking under an average stocking rate of 3 AU ha^{-1} and fertilisation of 100 kg N ha^{-1}; RS-4 is rotational stocking under an average stocking rate of 4 AU ha^{-1} and fertilisation of 200 kg N ha^{-1}; RS-5 is rotational stocking under an average stocking rate of 5 AU ha^{-1} and fertilisation of 300 kg N ha^{-1}.

Table 5
Average measured and FEI-weighted soil loss for vegetation and bare soil conditions.

Treatments	Vegetation cover		Bare soil	
	Measured SL ($mg\ s^{-1}\ m^{-2}$)	SL_w ($mg\ s^{-1}\ m^{-2}$)	Measured SL ($mg\ s^{-1}\ m^{-2}$)	SL_w ($mg\ s^{-1}\ m^{-2}$)
Cerrado	0.327	0.026	2.261	0.180
RS-3	2.213	0.148	18.070	1.228
RS-4	0.607	0.066	12.076	1.313
RS-5	0.300	0.032	5.786	0.627

Note: SL is the measured soil loss, and SL_w is the FEI-weighted soil loss. RS-3 is rotational stocking under an average stocking rate of 3 AU ha^{-1} and fertilisation of 100 kg N ha^{-1}; RS-4 is rotational stocking under an average stocking rate of 4 AU ha^{-1} and fertilisation of 200 kg N ha^{-1}; RS-5 is rotational stocking under an average stocking rate of 5 AU ha^{-1} and fertilisation of 300 kg N ha^{-1}.

the grazing management in RS-5 improved water infiltration by 20% and reduced soil loss by 78%. Considering bare soil plots, RS-5 presented SIR and SL_w similar to the Cerrado (α = 0.05); the RS-3 and RS-4 treatments did not present a significant improvement in water infiltration and erosion control. Therefore, compared with RS-3 and RS-4, RS-5 presented an improvement in water infiltration and soil erosion control even though we observed in this treatment an average stocking rate (5 AU ha^{-1}) of 24% and 59% higher than those found in RS-4 (4 AU ha^{-1}) and RS-3 (3 AU ha^{-1}) respectively (see Table 1 for the observed stocking rates from 2014 to 2018).

Average SIR and SL_w under vegetation cover were different from the results observed in the bare soil plots (α = 0.05), except the Cerrado with similar results for both conditions (Fig. 3). Higher SIR and lower SL_w were obtained under vegetation cover in all treatments. Particularly, water infiltration in RS-5 was higher than in the Cerrado under vegetation cover while soil loss this treatment was compared to the Cerrado under both vegetation and bare soil. Thus, our results suggest a possibility of increasing production with higher stocking rates while increasing infiltration and reducing soil loss. Higher stocking rates as in RS-5, when well managed and fertilised, do not compromise water infiltration and soil erosion. N fertilisation favours vegetation growth, which provides the soil more protection against the erosive power of rain (splash impact of raindrops). Higher vegetation cover contributes to increasing water infiltration and reducing soil loss.

4. Discussion

Variations in water infiltration and soil loss among treatments may be due to the treatment rather than the natural variability of soil characteristics since grazing management affects water infiltration and soil erosion by changing soil and vegetation variables (McGinty et al., 1979). Infiltration is a surface process defined, according to Brutsaert (2005), as the entry of water into the soil surface and its subsequent vertical motion through the soil profile. Thus, vegetation and topography conditions are key in the infiltration process. How each treatment was managed influenced soil physical and hydraulic properties and vegetation cover, which are important variables explaining water infiltration and soil erosion. Many studies have shown the importance of vegetation in water infiltration (Almeida et al., 2018; McGinty et al., 1979; Thompson et al., 2010), especially the related dry biomass and soil macroporosity (Falcão et al., 2020), to which water infiltration is more related (Sun et al., 2018). Further investigation will shed light on how much influence soil physical characteristics along with different management strategies have on water infiltration and soil erosion.

We see intensive grazing management as an opportunity to ensure food security and to settle conflicts of interest between agricultural development and nature protection (Sparovek et al., 2010; Spera, 2017). Using rotational and put-and-take stocking methods led to increased stocking rates while improving water infiltration and reducing soil erosion. Water infiltration improved and soil erosion reduced in the RS-5, in which we observed the highest stocking rates (Table 1) maintaining an adequate grazing pressure. Along with the stocking methods, we adopted a management strategy of using different N fertilisations according to site-specific conditions, which contributed to our findings. We observed that the grass clumps in RS-3 and RS-4 were sparser than in RS-5 corroborating no statistical differences in SIR and SL_w between RS-3 and RS-4 considering vegetated plots. Grass clumps absorb the animal impact on soil. Therefore, sparser clumps may have affected infiltration by increasing soil compaction and sealing due to livestock trampling. Beven and Germann (2013) found that grazing animals can destroy macropores close to the surface, compromising water infiltration into the soil.

Our results suggest that the management adopted affected not only vegetation cover but also the soil physical properties although we did not observe significant differences in the soil bulk density. Higher water infiltration and lower soil loss were observed in the treatment with higher stocking rates (RS-5) under both vegetation cover and bare soil

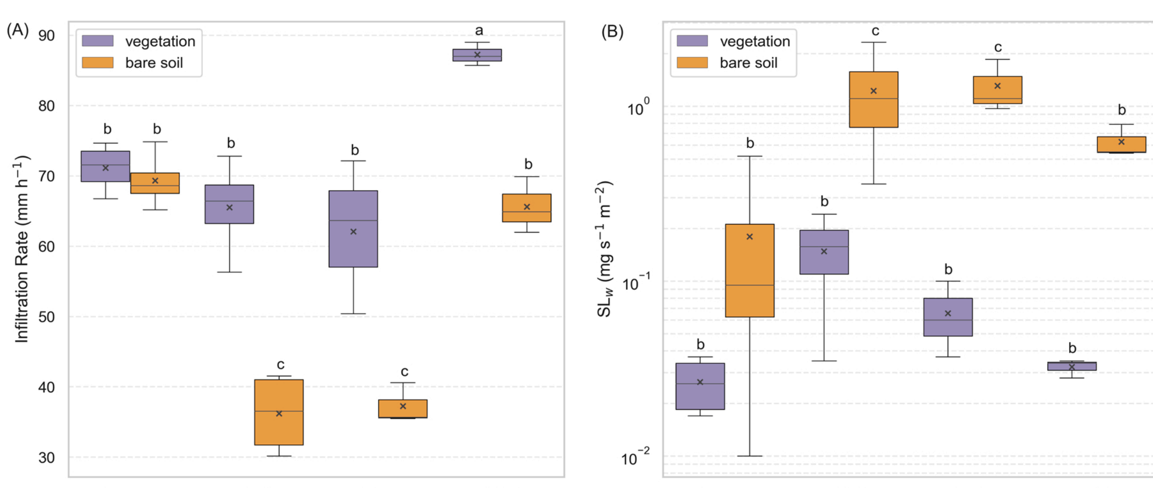

Fig. 3. Boxplots of (A) stable infiltration rate (SIR) ($mm\ h^{-1}$) and (B) the weighted soil loss ($mg\ s^{-1}\ m^{-2}$) under vegetation and bare soil conditions obtained from the Cerrado and the grazing treatments: rotational stocking under an average stocking rate of 3 AU ha^{-1} and Nitrogen fertilisation of 100 kg ha^{-1} (RS-3), an average stocking rate of 4 AU ha^{-1} and Nitrogen fertilisation of 200 kg ha^{-1} (RS-4), and an average stocking rate of 5 AU ha^{-1} and Nitrogen fertilisation of 300 kg ha^{-1} (RS-5). The following is shown: the 25th and 75th percentiles, the median with a line, the mean with a cross, and whiskers indicate the maximum and minimum values. Different letters indicate statistical different groups by the Scott Knott test (α = 0.05).

conditions. Positive impacts on soil physical properties corroborate the fact that water infiltration was higher under vegetation cover than under bare soil. Nitrogen fertilisation favours vegetation growth (Lavres and Monteiro, 2003) and indirectly benefits grazing management by increasing forage mass production allowing higher stocking rates (as observed in RS-5) since micronutrients are adequate (Table 2). More forage production may have also increased, for instance, root density facilitating water infiltration into the soil by improving soil physical structure. Furthermore, vegetation prevents the soil from soil crusting/sealing due to the raindrop splash effect resulting in lower infiltration rates.

Rigorous soil and animal management were key to increasing production (Euclides et al., 2018, 2016; Gurgel, 2019) while reducing soil and water losses. The fact that cattle rotates among paddocks (rotational stocking) with adaptive stocking rates according to vegetation availability (put-and-take stocking) improved soil erosion control and water infiltration. Drewry (2006) observed that soil naturally recovers its properties and structure after total or partial animal exclusion from the pasture. Donkor et al. (2002) reported that the same degree of soil compaction can be achieved by smaller numbers of animals grazing for a longer period or many animals grazing for a short period. Intensive grazing with reduced negative environmental impacts is only possible for managing grazing and soil, therefore there is a balance between the vegetation availability (herbage accumulation) and stocking rate.

One of the greatest challenges of raising beef cattle is to identify the productive limits of forage. Pasture canopy height is fundamental to determine rotation among paddocks and to allow soil recovery, as well as to protect the soil against water erosion. On one hand, more forage accumulation protects the soil from splash erosion and grazing trampling effects resulting in less soil disaggregation and transport. On the other hand, higher forage intake and animal performance depend on identifying the optimal time to interrupt grazing; it leads to preventing not only economic loss but also wastage and land degradation. Start and stop grazing heights are of paramount importance to not only ensure animal intake of the maximum nutritive value but also improve water infiltration and to reduce soil loss. In the next paragraphs, we will provide thoughts on possible socioeconomic impacts on the Brazilian and global context comparing the grazing system studied with other similar systems.

4.1. Environmental and socioeconomic impacts

Our findings show that rotational stocking together with the put-and-take stocking and N fertilisation is a feasible alternative to sustain productivity, economic growth, and environmental conservation as there is adequate management of animal and pastureland, corroborating Kothmann (2009). Managing pastures that support heavier stocking rates without degrading soil (maintaining the optimal grazing pressure) is a goal for ensuring water, food, and energy security nexus. Our results were achieved using minimal Nitrogen fertiliser doses for forage maintenance, according to the agronomic recommendation (Pereira et al., 2018). In turn, our findings impact several economic sectors that directly and indirectly depend on agriculture. Socioeconomic development has been noticed in the Cerrado due to the practice of intensive agriculture since there is a substantial investment in education and technology (VanWey et al., 2013). The government needs to incentivise intensive agriculture to meet its production goal while providing socio-economic benefits and sparing what is left of the Cerrado vegetation.

We suggest adopting the stocking methods and N fertilisation we presented in, for example, part of the farm's area as an alternative to overcoming drought periods as management under optimal grazing pressures allows adequate forage heights for animal consumption. In contrast to continuous stocking, rotational stocking has shown some positive effects on livestock productivity and pasture quality. On the other hand, di Virgilio et al. (2019) found that the Savory Grazing Method (SGM) presented negative effects on livestock productivity; the authors also found that the stocking rate is one of the main variables affecting livestock productivity. Deferred stocking is a method for postponing grazing to provide time for vegetation recovery. Thus, it is not a practice for increasing productivity (Allen et al., 2011), but it aims at restoring and maintaining the desired condition of grazing land by the delay of grazing on land units. Notwithstanding, it is important to highlight that researchers should focus on identifying the suitable stocking method and management strategy for local-specific conditions. Grazing processes require advancements to support adaptive management allowing decision-makers to achieve their goals according to their needs and environment.

In the Brazilian context, there is a significant drought period during the winter in the central-west and southeast, which are leading agricultural regions; therefore, maintaining high stocking rates throughout the year becomes unsustainable due to water shortages. Therefore, farmers have the possibility of managing cattle in part of their properties under intensive grazing during the rainy season while the other area may recover the vegetation cover and increase herbage accumulation for supporting grazing during the dry season. It is of paramount importance to have an appropriate site-specific stocking method in this other part of the property to avoid soil and pasture degradation, which may cause a decrease in livestock production. Besides the grazing pressure, precipitation and livestock type have been related to the main variables that may affect vegetation in the rotational stocking (di Virgilio et al., 2019).

There are approximately 158 million ha of pasturelands in Brazil with an average of 1 AU ha^{-1} (Brazilian Institute of Geography and Statistics (IBGE), 2017), in which about 30 million ha are degraded pastures or under a degradation process (IPEVS, 2012). Here, we found an opportunity to restore part of those degraded pasture areas with a 5-fold increase in beef cattle production (AU ha^{-1}) according to the average stocking rate observed in RS-5 compared with the current average stocking rate in Brazil. Strassburg et al. (2014) found that an increase of 20% in pasture productivity would allow Brazil to meet the food-energy nexus demand until 2040. This modification in the production system would mean saving land as fewer areas would be expanded for livestock; consequently, it would halt the conversion of the Cerrado into agricultural land through deforestation. Furthermore, soil conservation practices along with rigorous agricultural management are of paramount importance to achieving the recovery of degraded land without compromising water infiltration and favouring soil erosion.

Brazil plays an important role in agricultural exportation so that an increase in beef production would have a global impact on meeting the ever-increasing global food demand. Barbosa (2018) showed that a 3-fold increase in the N dose as in RS-5 can raise the live weight of steers per hectare by 98% while we found an increase in water infiltration of 33% and a reduction in soil erosion of 78% in vegetated plots. This production increase combined with proper soil conservation practices and agricultural management was fundamental to ensure the sustainability we showed in this study. Moreover, achieving a level of production increase while decreasing water footprint and sparing native vegetation would leverage exportations due to green certifications required for some countries. Governments need to focus agricultural development on mechanisms to support sustainable intensive agriculture.

Research needs to advance some limitations that our work presents. Even though we carried out our tests in the major soil order in Brazil (Oxisol) covering 32% of the territory (Santos et al., 2011), different soil orders are limitations and may provide different water infiltration and soil loss results from those we present here. A grazing system is site-specific since it integrates specific soil, plant, animal, social, as well as economic features and stocking methods. Analysing the excess of Nitrogen in runoff would also add interesting implications in terms of adopting different fertilisation strategies. Additionally, we encourage further investigations in changes in evapotranspiration as many studies have shown the effects of pasturelands on this variable (Anache et al., 2019; Nóbrega et al., 2017; Spera et al., 2016).

5. Conclusion

We investigated soil erosion and water infiltration in pastures under sustainable intensive grazing management with three different stocking rates by using rotational and put-and-take stocking methods with different Nitrogen application rates. We carried out 28 rainfall simulations with rainfall intensities varying according to the treatments studied: rotational stocking (RS) with a mean stocking rate of 3 AU ha^{-1} (RS-3), 4 AU ha^{-1} (RS-4), and 5 AU ha^{-1} (RS-5). Our findings indicate that sustainable intensification management is an opportunity to meet global food demand maintaining the soil in good conditions as adequate stocking rates are adopted aiming at optimal grazing pressures. The stocking methods we presented provided a higher infiltration rate and lower soil loss in the system with the highest stoking rate but also at a higher N application rate that maintained the vegetation cover.

Pastures can be more productive if soil and water conservation practices were adopted along with agricultural management. Migrating part of their properties to intensive grazing practices, farmers have the possibility of having a 5-fold increase in beef cattle production since soil and grazing management is adequate. Moreover, this change in how grazing lands are managed contributes to making the system more resilient, mainly during water shortage periods. Systems with heavier grazing intensities have water infiltration and soil loss comparable with results observed in the Cerrado. The adequate stocking rate with N fertilisation to maintain vegetation cover, forage utilisation, and rest period are of paramount importance to the results we observed. Therefore, livestock production needs site-specific management that allows seasonal adaptation depending on drought periods, especially with the changing climate.

We presented the quantitative aspects of the main variables here related to land degradation. However, qualitative aspects related to the excess of Nitrogen in runoff would be an advance in halting land degradation and improving water and food security as Nitrogen fertilisation indirectly increased water infiltration and reduced soil erosion in a medium texture soil, Oxisol. Furthermore, future research will have the possibility to observe whether soil loss and runoff vary seasonally from the results we present here, as well as the impact of this agricultural production on water cycling (mainly evapotranspiration). Additionally, we carried out the simulations during the residual effect of fertilisation on soil, so that finding an optimal interval period for applying fertilisers without compromising production and soil is a research possibility.

Declaration of Competing Interest

The authors report no declarations of interest.

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